

MARS EXPLORATION ROVER APXS RESULTS FROM MATIJEVIC HILL. B. A. Cohen¹, B. C. Clark², R. Gellert³, G. Klingelhöfer⁴, D. W. Ming⁵, D. W. Mittlefehldt⁵, R. V. Morris⁵, C. M. Schrader¹, C. Schröder⁶, A. S. Yen⁷, T. Economou⁸, P. de Souza⁹, B. L. Jolliff¹⁰, R. A. Arvidson¹⁰, S. W. Squyres¹¹, and the Athena Science Team. ¹NASA MSFC, Huntsville AL (Barbara.A.Cohen@nasa.gov), ²Space Science Institute, Boulder CO; ³University of Guelph, Guelph, Canada; ⁴J. Gutenberg-Universität, Mainz, Germany; ⁵NASA JSC, Houston TX; ⁶Universität Tübingen, Tübingen, Germany; ⁷Jet Propulsion Laboratory, Pasadena CA; ⁸University of Chicago, Chicago IL; ⁹University of Tasmania, Australia; ¹⁰Washington University, St. Louis MO; ¹¹Cornell University, Ithaca NY.

Introduction: On sol 2681, Opportunity crossed from Burns formation sandstones to the high-standing, older rocks surrounding the rim of Endeavour crater at Cape York, a ridge of exposed bedrock and ejecta on the crater's western rim. The rocks along Cape York's western slopes are discussed in [1].

Clastic Endeavour crater impactites are collectively called the Shoemaker Formation, postulated to be analogous to the suevites and airfall breccias found around the rim of the Ries Crater in Germany. Shoemaker Formation rocks are overall basaltic in nature, with compositional trends and overall similarities to typical Gusev basalts, Martian basaltic meteorites, and the basaltic sand typical of the Meridiani region.

A rock unit ringing the base of Cape York was investigated at Deadwood and again at Grasberg, at Cape York's northern tip. This unit is bright-toned with platy, millimeter-scale layering. Its elemental composition is intermediate between the rocks of the Shoemaker formation and the Burns Formation, with elevated Ca and S concentrations, interpreted as a clastic sedimentary rock formed by erosion of the Shoemaker Formation and later modified to create the S enrichment. The Deadwood/Grasberg unit hosts cm-thick veins, typified by one named Homestake, having APXS compositions dominated by CaSO₄, with minor Na₂SO₄, phosphate, and Cl-containing salt.

Eastern Traverse: Opportunity rounded the northern tip of Cape York and traversed southward along the crater (eastern) side of Cape York, which Pancam and Navcam data indicate is topographically downslope and possibly downsection from the Shoemaker Formation. In an effort to understand the eastern side stratigraphy, a loop around an area called Matijevic Hill was taken. The Matijevic hill area includes a relatively bright, recessive deposit termed Whitewater Lake and a series of more-resistant, darker toned benches (Kirkwood, Copper Cliff) [2,3]. Overall, the "country rock" is very similar to typical Martian basaltic soils, e.g., Laguna class soils [4] (Fig. 1).

The topographically lower bench, exemplified by the Kirkwood outcrop, is dominated by millimeter-size spherules. Unlike the hematite-rich concretions of Meridiani Planum, the Kirkwood spherules have internal structure and resistant rims [5]. Two APXS spectra were gathered on a vertical surface, containing both

spherules and groundmass, before and after the RAT brush was used. The brushing had little effect because of the rough topography; both spectra were nearly identical. Relative to basaltic soil, Kirkwood has higher Si (50% SiO₂) and Mg (~9% MgO), lower Fe and Zn, and lower Mn/Fe, indicating high amounts of Fe³⁺. However, SO₃ is low (4% SO₃) compared with Martian soils. The low FeO content suggests that the spherical concretions are not hematite-rich (spectra on Meridiani rocks with comparable areal exposure of hematite berries yielded 30% FeO). The origin of the Kirkwood outcrop is uncertain, but the spherules may have formed as lapilli of impact or volcanic origin, devitrification spherules, or concretions. Opportunity is planning to revisit an Kirkwood-type outcrop to further investigate the nature and origin of these spherules.

The topographically upper bench unit is called Copper Cliff, which appears to be a matrix-supported breccia with angular clasts up to a few cm, tiny veins, and some Kirkwood-type spherules sprinkled throughout. Three as-is APXS targets were investigated along Copper Cliff: Onaping (a vertical face), Vermilion Cliffs (an oblique face), and Vermilion Lake (the flat-lying top of the unit). Of these, Vermilion Lake was the only with significant dust cover. All three analyses were very similar to each other, showing Copper Creek is a largely basaltic breccia (Fig. 1).

Between the two benches is a widespread, slope-forming, light-toned rock broadly called Whitewater Lake that Opportunity investigated in several locations. The Whitewater Lake unit is very fine-grained and occasionally contains small clasts and spherules. The Whitewater Lake outcrops map to locations where

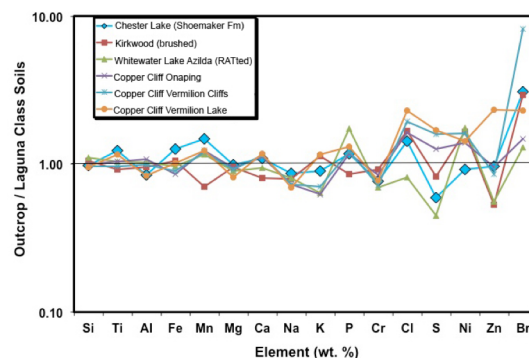


Fig. 1. APXS compositions of Matijevic Hill outcrops compared with Laguna-class basaltic soils from Gusev crater.

CRISM data indicates the presence of smectite [4]. APXS data were acquired for a number of Whitewater Lake targets, including natural, brushed, and RATted outcrop. The main bedrock (Azilda) is broadly basaltic, with most elements within $\pm 10\%$ of soil, but the surface contains higher amounts of S, Cl, K, Zn, and Br, elements that decline after brushing and RATting (Fig. 2a). APXS data do not show excess light elements for these outcrops, though they are slightly enriched in Al and Si relative to other Cape York rocks.

A more resistant, ~ 1 mm thick, darker-toned coating or planar joint fill patchily covers much of the Whitewater Lake outcrops. This coating (Chelmsford, Sandcherry) is poorer in Al and Si than the bedrock, but richer in Mg, Ca, Zn, and Fe (Fig. 2b). The minor elements S, Cl, Zn, and Br appear much higher in the coating; this could be due in part to the fact that these targets were incompletely brushed and likely contained dust in the field of view. However, Mn is also higher in the Chelmsford coating, which is a major chemical variation indicating that redox/pH conditions favored Mn concentration (Fig. 1b). Mn is not correlated with dust but is slightly enriched in the Whitewater Lake surface analyses, and may indicate that exposed surfaces on Whitewater Lake are higher in Mn due to their interaction with the coating or joint fill material.

Boxwork veins, thinner and more branching than the Homestake veins, occur throughout Whitewater Lake. Opportunity is continuing to search for veins that provide a clean surface and that fill the APXS

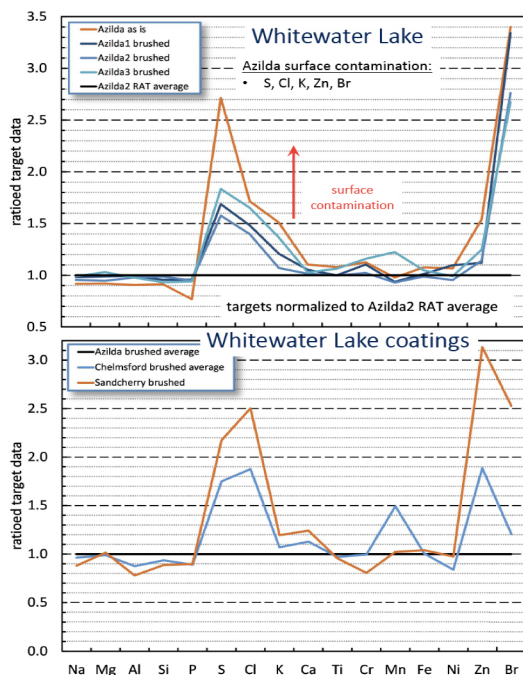


Fig. 2. a) APXS data of Whitewater Lake bedrock as it was progressively analyzed as-is, RAT brushed, and RAT ground. b) Coatings on Whitewater Lake relative to the groundmass.

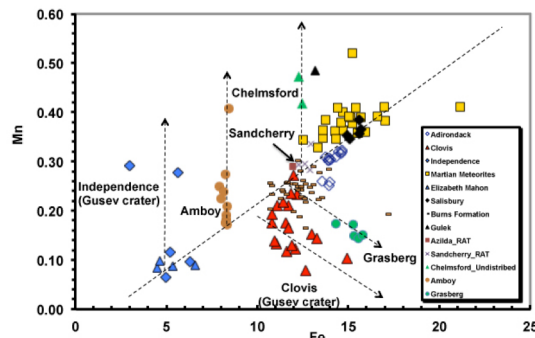


Fig. 3. APXS data trends of Fe vs Mn for Cape York rocks and selected other comparisons.

field-of-view to understand these veins.

Discussion: Correlation analysis of APXS results on the eastern slope rocks indicate that the Matijevec Hill rocks are overall compositionally distinct from the Shoemaker Formation rocks [6]. Compared to the Shoemaker impactites, Matijevec Hill rocks are higher in Al, Si, and Ni, and lower in Ti, Fe, and Zn. No significant variation is evident in the APXS analyses that indicate the presence of a smectite or other phyllosilicate, as opposed to basaltic rocks. However, APXS data cannot in themselves rule out phyllosilicates. If indeed this material contains smectite, as seen from orbit, it implies that the rock has been isochemically altered to create the phyllosilicate content.

The Cl content of the Cape York rocks is relatively high, and whereas the S/Cl ratio in the Burns Formation is 4x higher than in soil, in the Cape York rocks it is lower than in soil. These trends indicate that the alteration processes and types of aqueous salt loads were different between Cape York and Meridiani. In addition, significant deviations from the Martian Mn/Fe ratio are observed in Whitewater Lake coatings and the altered Grasford/Deadwood rocks (Fig. 3). These variations indicate that the redox/pH conditions during alteration of the Shoemaker Formation rocks and the Matijevec Hill rocks were similar, but that the Deadwood/Grasberg unit may have undergone alteration under different conditions, possibly at a later time.

The Matijevec Hill outcrops appear to share a common genetic origin. It is not yet clear whether both the Shoemaker impactites and Matijevec Hill rocks are related to the formation of Endeavour Crater, or whether the Matijevec Hill suite represents a prior episode of Martian impact or volcanism. Opportunity continues to investigate both hypotheses.

References: [1] Squyres et al. (2012) *Science* **336**, 570-576. [2] Squyres et al. (2013) *LPSC* **44**. [3] Crumpler et al. (2013) *LPSC* **44**. [2] Ming et al. (2008) *JGR*, doi:10.1029/2008JE003195. [3] Herkenhoff et al. (2013) *LPSC* **44**. [4] Arvidson et al. (2013) *LPSC* **44**.